CLAIMS

WHAT IS CLAIMED IS:

1. A control method for use with a crystal puller for growing a monocrystalline semiconductor crystal according to the Czochralski process, said crystal puller having a heated crucible containing a semiconductor melt from which the crystal is grown at a growth rate V_g, said melt having a surface forming a meniscus adjacent the crystal, said crystal puller further having a heater supplied by a power supply for heating the crucible, said crystal being grown on a seed crystal pulled from the melt at a pull rate V_p, said method comprising the steps of:

defining an interval of time for observing growth of the crystal being pulled from the melt;

determining variations in crystal diameter occurring during the observation interval;

estimating a current value of the growth rate V_{gf} as a function of the determined variations in crystal diameter;

estimating a current steady-state value of the growth rate V_{gs} as a function of the estimated growth rate V_{gf} at the end of the observation interval;

determining a pull rate parameter as a function of the estimated steady-state growth rate V_{gs}, said pull rate parameter being representative of an incremental change in the pull rate V_p to effect a desired change in the diameter of the crystal toward a target diameter;

determining a heater power parameter as a function of the estimated steady-state growth rate V_{gs}, said heater power parameter being representative of an incremental change in the power supplied to the heater to effect a desired change in the growth rate of the crystal toward a target growth rate, said pull rate parameter and said heater power

parameter being determined independently of a temperature condition sensed during pulling; and

adjusting the pull rate V_p according to the pull rate parameter and adjusting the power supplied to the heater by the power supply according to the heater power parameter thereby minimizing variations in both crystal diameter and growth rate during subsequent growth of the crystal following the observation interval.

2. The method of claim 1 further comprising repeating the step of determining variations in crystal diameter for N observation intervals.

3. The method of claim 2 wherein the steps of determining the heater power parameter and adjusting the power supplied to the heater occur after every N observation intervals.

4. The method of claim 2 further comprising repeating the steps of determining the pull rate parameter and adjusting the pull rate for each of the N observation intervals.

5. The method of claim 2 wherein the step of adjusting the pull rate occurs at the end of each observation interval.

6. The method of claim 2 further comprising the step of accumulating values of the estimated steady-state growth rate V_{gs} over the N observation intervals.

7. The method of claim 6 wherein the step of estimating the steady-state growth rate V_{gs} includes estimating a current steady-state value of the growth rate V_{gs} as a function of the N accumulated values of the estimated steady-state growth rate V_{gs} and wherein the step of adjusting the pull rate includes controlling the pull rate V_p as a function of the

estimated steady-state growth rate V_{gs} to minimize subsequent variations in crystal diameter relative to the target diameter.

8. The method of claim 7 wherein the step of adjusting the power supplied to the heater by the power supply includes adjusting the power so that the estimated steady-state growth rate V_{gs} is approximately equal to a predetermined target growth rate V_{set}.

9. The method of claim 7 wherein the step of adjusting the power supplied to the heater by the power supply includes defining a power increment δP according to:

$$\delta P = -(V_{gs} - V_{set}) / A_p;$$

and applying said power increment δP to the crystal puller for adjusting the heat of the crucible to cause the estimated steady-state growth rate V_{gs} to move toward a desired growth rate set value V_{set}; and

where A_p is a predetermined power response coefficient.

10. The method of claim 9 wherein the power response coefficient A_p is defined by a derivative of the estimated steady-state growth rate V_{gs} relative to the power supplied to the heater.

11. The method of claim 1 wherein the length of the observation interval is inversely related to a predetermined height response coefficient A_h.

12. The method of claim 1 wherein the step of estimating a current steady-state value of the growth rate V_{gs} comprises:

defining a function r(t) based on the variations in crystal diameter occurring during the observation interval, said function r(t) being representative of radius variations and

being a function of crystal radius r, meniscus height h and growth rate V_g with respect to time; and

performing a best fit routine on the function r(t) to deduce current values of crystal radius r_f, meniscus height h_f and growth rate V_{gf} at the end of the observation interval.

13. The method of claim 12 wherein the step of performing the best fit routine includes defining the function r(t) as:

$r(t) = r_f + A[Y(h_f - h_s)x + (Y + h_f - h_s)Z(x + 1 - e^x) + Z^2(x + 1.5 - 2e^x + 0.5e^{2x})]$;

where $x = A_h t$; $Y = V_{gf}/A_h$; $Z = (V_p - V_{gf})/A_h$; and $A = 2h_s/a^2$; and

where A_h is a predetermined height response coefficient; the time t is counted back from the end to the start of the observation interval; h_s is a steady-state meniscus height; and a is a capillarity parameter.

14. The method of claim 1 wherein the step of determining the pull rate parameter includes predicting a new value of V_p to reduce subsequent variations in crystal diameter and maintain the meniscus height approximately constant.

15. The method of claim 1 further comprising the steps of determining a set of control parameters for a fraction of crystal growth following the initial observation interval as a function of the variations in crystal diameter during the observation interval and controlling the growth of the crystal as a function of the control parameters.

16. The method of claim 15 wherein the set of control parameters comprises a height response coefficient A_h and a power response coefficient A_p.

17. The method of claim 16 wherein the height response coefficient A_h is defined by a derivative of the growth rate V_g relative to meniscus height h.

18. The method of claim 16 wherein the power response coefficient A_p is defined by a derivative of the estimated steady-state growth rate V_{gs} relative to the power supplied to the heater.

19. The method of claim 1 further comprising the step of pulling the growing crystal from the melt at a first target pull rate during the observation interval, said first target pull rate being substantially constant.

20. A control method for use with a crystal puller for growing a monocrystalline semiconductor crystal according to the Czochralski process, said crystal puller having a heated crucible containing a semiconductor melt from which the crystal is grown at a growth rate of V_g, said melt having a surface forming a meniscus adjacent the crystal, said crystal puller further having a heater supplied by a power supply for heating the crucible, said crystal being grown on a seed crystal pulled from the melt at a pull rate V_p, said method comprising the steps of:

defining an interval of time for observing growth of the crystal being pulled from the melt;

determining variations in crystal diameter occurring during the observation interval;

defining a function r(t) based on the variations in crystal diameter occurring during the observation interval, said function r(t) being representative of radius variations and being a function of current values of crystal radius r, meniscus height h and growth rate V_g with respect to time;

performing a best fit routine on the function r(t) to deduce the current values of crystal radius r_f, meniscus height h_f and growth rate V_{gf} at the end of the observation interval;

calculating a current steady-state value of the growth rate V_{gs} as a function of the deduced current values of crystal radius r_f, meniscus height h_f and growth rate V_{gf} at the end of the observation interval and independent of melt temperature and meniscus height sensed during pulling; and

controlling the crystal puller as function of current steady-state growth rate V_{gs} to minimize variations in both crystal diameter and growth rate during subsequent growth of the crystal.

21. A control method for use with a crystal puller for growing a monocrystalline semiconductor crystal according to the Czochralski process, said crystal puller having a heated crucible containing a semiconductor melt from which the crystal is grown at a growth rate V_g, said melt having a surface forming a meniscus adjacent the crystal, said crystal puller further having a heater supplied by a power supply for heating the crucible, said crystal being grown on a seed crystal pulled from the melt at a pull rate V_p, said method comprising the steps of:

defining an interval of time for observing growth of the crystal being pulled from the melt;

determining variations in crystal diameter occurring during the observation interval;

estimating a current value of the growth rate V_{gf} as a function of the determined variations in crystal diameter;

estimating a current steady-state value of the growth rate V_{gs} as a function of the estimated growth rate V_{gf} at the end of the observation interval and independent of meniscus height measured during pulling;

determining a pull rate parameter as a function of the estimated steady-state growth rate V_{gs}, said pull rate parameter being representative of an incremental change in the pull rate V_p to effect a desired change in the diameter of the crystal toward a target diameter;

determining a heater power parameter as a function of the estimated steady-state growth rate V_{gs}, said heater power parameter being representative of an incremental change in the power supplied to the heater to effect a desired change in the growth rate of the crystal toward a target growth rate; and

adjusting the pull rate V_p according to the pull rate parameter and adjusting the power supplied to the heater by the power supply according to the heater power parameter thereby simultaneously minimizing variations in both crystal diameter and growth rate during subsequent growth of the crystal following the observation interval.

22. The method of claim 21 further comprising repeating the step of determining variations in crystal diameter for N observation intervals and accumulating values of the estimated steady-state growth rate V_{gs} over the N observation intervals.

23. The method of claim 22 wherein the steps of determining the heater power parameter and adjusting the power supplied to the heater occur after every N observation intervals.

24. The method of claim 22 further comprising repeating the steps of determining the pull rate parameter and adjusting the pull rate for each of the N observation intervals.

25. The method of claim 22 wherein the step of adjusting the pull rate occurs at the end of each observation interval.

26. The method of claim 22 wherein the step of estimating the steady-state growth rate V_{gs} includes estimating a current steady-state value of the growth rate V_{gs} as a function of the N accumulated values of the estimated steady-state growth rate V_{gs} and wherein the step of adjusting the pull rate includes controlling the pull rate V_p as a function of the

estimated steady-state growth rate V_{gs} to minimize subsequent variations in crystal diameter relative to the target diameter.

27. The method of claim 26 wherein the step of adjusting the power supplied to the heater by the power supply includes adjusting the power so that the estimated steady-state growth rate V_{gs} is approximately equal to a predetermined target growth rate V_{set}.

28. The method of claim 26 wherein the step of adjusting the power supplied to the heater by the power supply includes defining a power increment δP according to:

$$\delta P = -(V_{gs} - V_{set}) / A_p;$$

and applying said power increment δP to the crystal puller for adjusting the heat of the crucible to cause the estimated steady-state growth rate V_{gs} to move toward a desired growth rate set value V_{set}; and

where A_p is a predetermined power response coefficient defined by a derivative of the estimated steady-state growth rate V_{gs} relative to the power supplied to the heater.

29. The method of claim 21 wherein the length of the observation interval is inversely related to a predetermined height response coefficient A_h defined by a derivative of the growth rate V_g relative to meniscus height h.

30. The method of claim 21 wherein the step of estimating a current steady-state value of the growth rate V_{gs} comprises:

defining a function r(t) based on the variations in crystal diameter occurring during the observation interval, said function r(t) being representative of radius variations and being a function of current values of crystal radius r, meniscus height h and growth rate V_g with respect to time; and

performing a best fit routine on the function r(t) to deduce the current values of crystal radius r_f, meniscus height h_f and growth rate V_{gf} at the end of the observation interval.

31. The method of claim 30 wherein the step of performing the best fit routine includes defining the function r(t) as:

$$r(t) = r_f + A[Y(h_f - h_s)x + (Y + h_f - h_s)Z(x + 1 - e^x) + Z^2(x + 1.5 - 2e^x + 0.5e^{2x})];$$

where $x = A_h t$; $Y = V_{gf}/A_h$; $Z = (V_p - V_{gf})/A_h$; and $A = 2h_s/a^2$; and

where A_h is a predetermined height response coefficient; the time t is counted back from the end to the start of the observation interval; h_s is a steady-state meniscus height; and a is a capillarity parameter.

32. The method of claim 21 wherein the step of determining the pull rate parameter includes predicting a new value of V_p to reduce subsequent variations in crystal diameter and maintain the meniscus height approximately constant.